Implications of Fluid Dynamics Inside Arctic Sea Ice Sheets for Thermohaline Circulation and Biological Activity

Chris Petrich[1,2], Pat J. Langhorne[1], and Hajo Eicken[2]

[1] University of Otago, Department of Physics, Dunedin, New Zealand

[2] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA

1. Summary

Background:

- Growing sea ice is a source of dense brine
- Arrangement of brine inclusions during growth may be crucial for meltwater drainage in summer
- Permeability and porosity at the ice–water interface constrain nutrient fluxes

Aim:
Characterize the modelled structure of growing sea ice, then extend investigation to melt season. Here: How can the sea ice salinity (and salt flux during ice growth) be parameterized? How big is the nutrient flux into the ice during growth? How does the continuum fluid dynamics model cope with coarse and fine grid sizes?

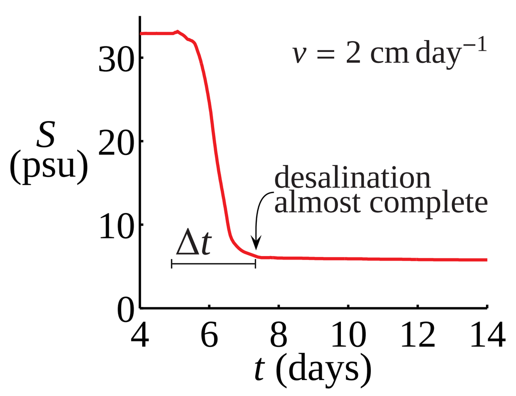
Method:

- Treat sea ice as porous medium, porosity f (continuum approach)
- 2-dimensional finite volume fluid dynamics simulations
  - impose oceanic heat flux F_w
  - impose heat exchange with atmosphere
  - find empirical relationship for stable sea ice salinity S
  - determine the mass flux from ocean to sea ice

2. Overview

Desalination occurs

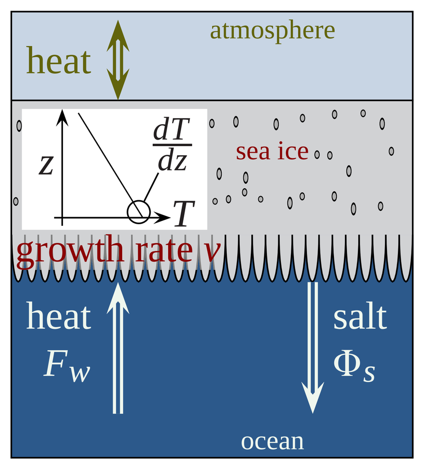
- over a relatively short period of time (Δt) after initial freezing
- close to the ice–ocean interface



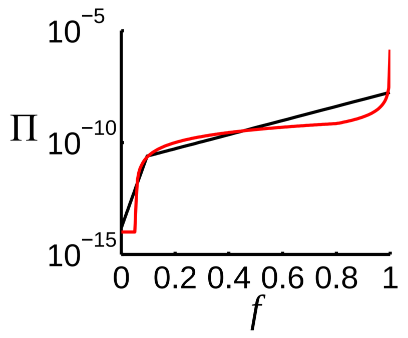
Simulated desalination 0.3 m below the ice–air interface.

Energy balance at the ice–ocean interface:

$$F_w - \underbrace{v\rho L(1-f)}_{<0} + \underbrace{k\frac{dT}{dz}}_{<0} = 0$$

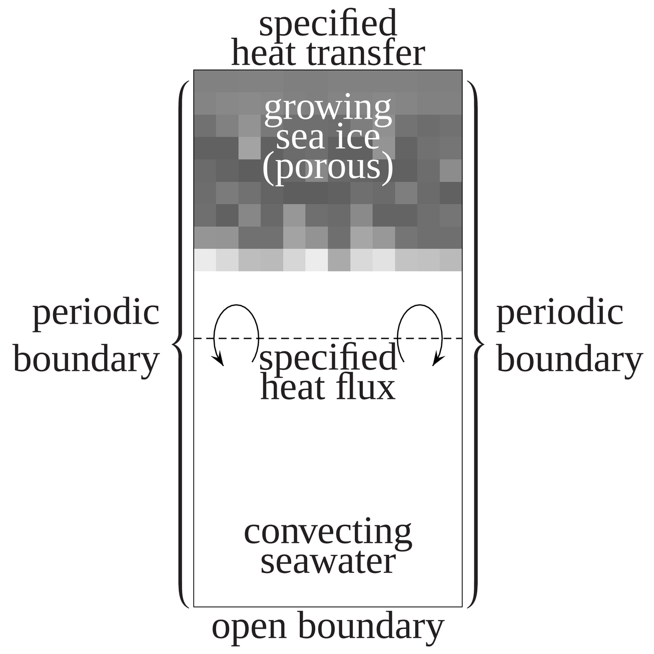


Fluid dynamics simulations use a permeability–porosity relationship similar to *Petrich et al.* (2006) (red) or *Eicken et al.* (2004) (black).



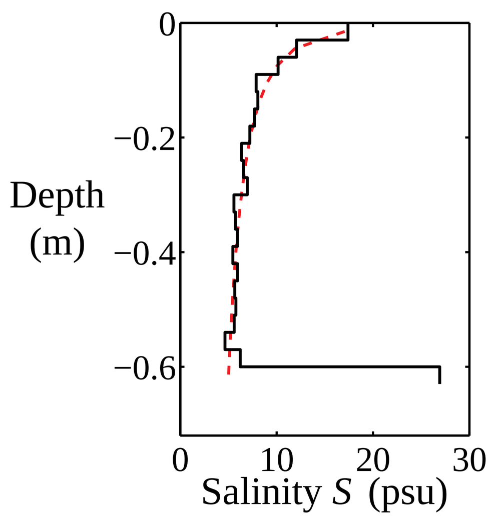
3. Computational domain

- Oceanic heat flux
  - imposed 0.1 to 0.2 m below the sea ice–ocean interface
  - enforced by adjusting the temperature of upwelling water
- Sea ice–atmosphere interface: constant T, or constant dT/dz
- Domain is periodic horizontally

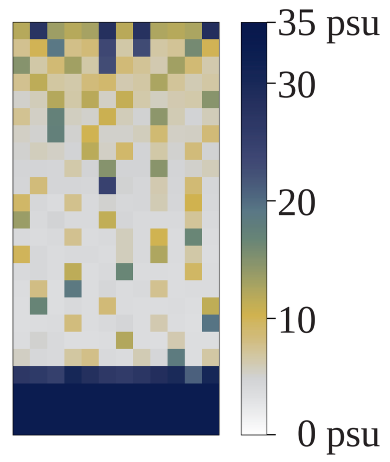


4. Salinity profile

- Ice–air interface temperature −20 °C
- Oceanic heat flux F_w = 0 Wm^{-2}

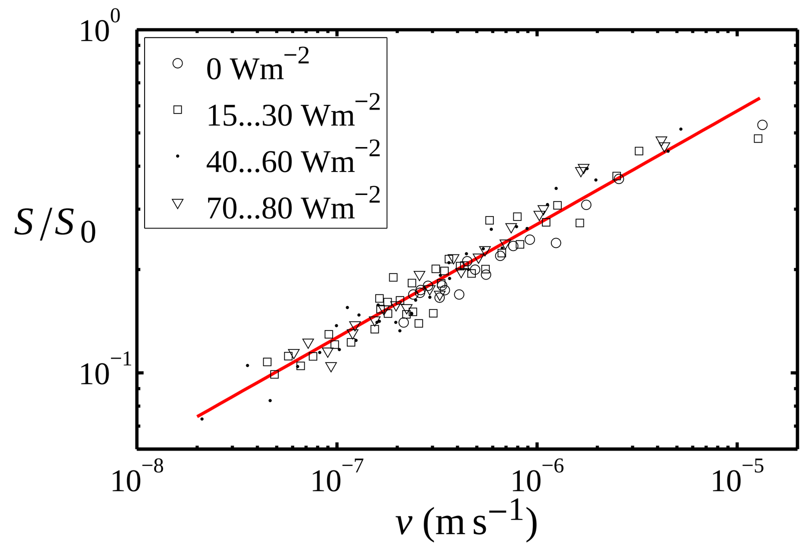


Average salinity profile (solid line), and parameterization (dashed line) from Equation (1).



Corresponding vertical salinity profile.

5. Modeled stable salinity

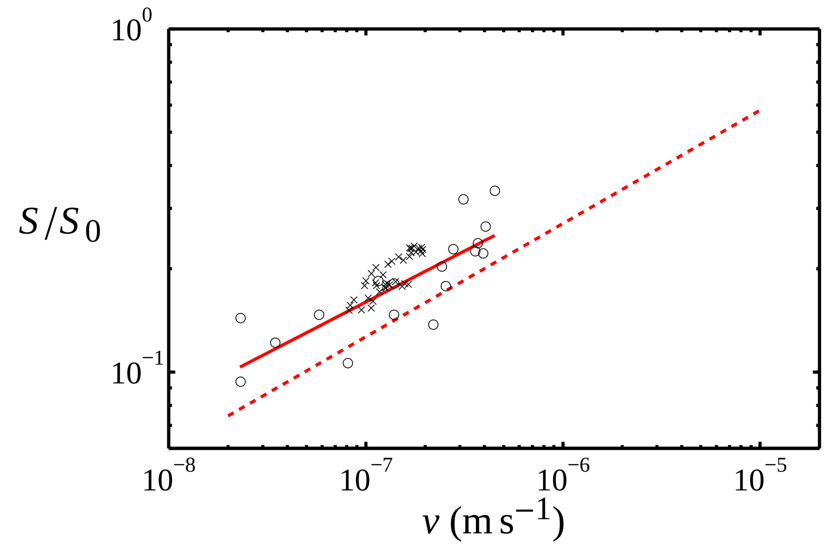


Simulated ratio between stable salinity S and seawater salinity S_0 as a function of growth rate v. The solid line follows

$$\frac{S}{S_0} = 0.14\left(\frac{v}{1.35\times10^{-7}\ \mathrm{m\,s^{-1}}}\right)^{0.33}. \quad (1)$$

The stable salinity of growing sea ice can be predicted based on the growth velocity, independent of oceanic heat flux.

6. Stable salinity data



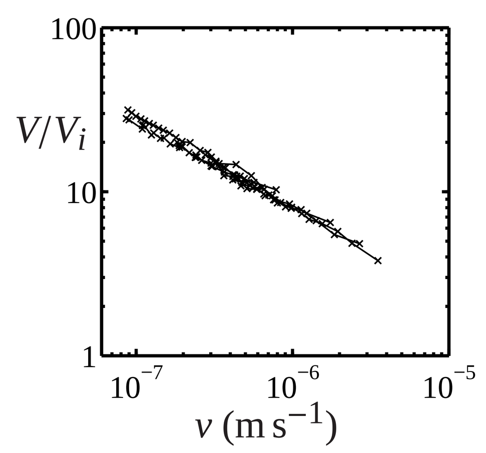
Measured ratio between stable salinity S and seawater salinity S_0 as a function of growth rate v of *Granskog et al.* (in press) (circles) and *Nakawo and Sinha* (1981) (crosses). The broken line follows Equation (1).
The best–fit power law to data of *Granskog et al.* (in press) is (solid line)

$$\frac{S}{S_0} = 0.18\left(\frac{v}{1.35\times10^{-7}\ \mathrm{m\,s^{-1}}}\right)^{0.30}. \quad (2)$$

7. Ocean–sea ice mass flux

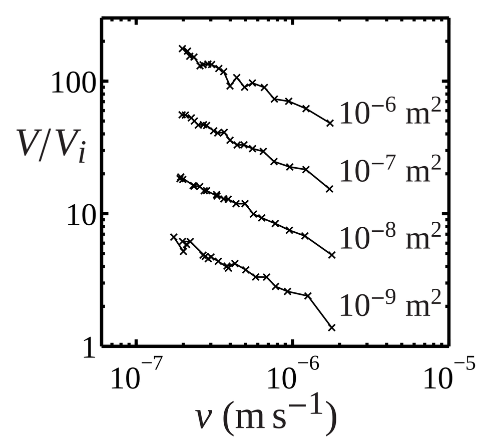
Preliminary estimate of an upper limit for the availability of nutrients: each volume of sea ice V_i is penetrated by a volume of ocean water V during growth.

Ratio V/V_i from a typical permeability parameterization (after *Eicken et al.* (2004), cf. Box 2). Various grid sizes and surface temperatures. F_w = 0 W m^{-2}.



- If all nutrients of the seawater are retained in the sea ice matrix through biological processes, then the effective nutrient loading in the ice may be several hundred times higher than that of a corresponding volume of ocean water.
- Further, if nutrients percolate toward the sea ice–ocean interface then the nutrient loading may exceed the value in the ocean by 3 to 4 orders of magnitude.

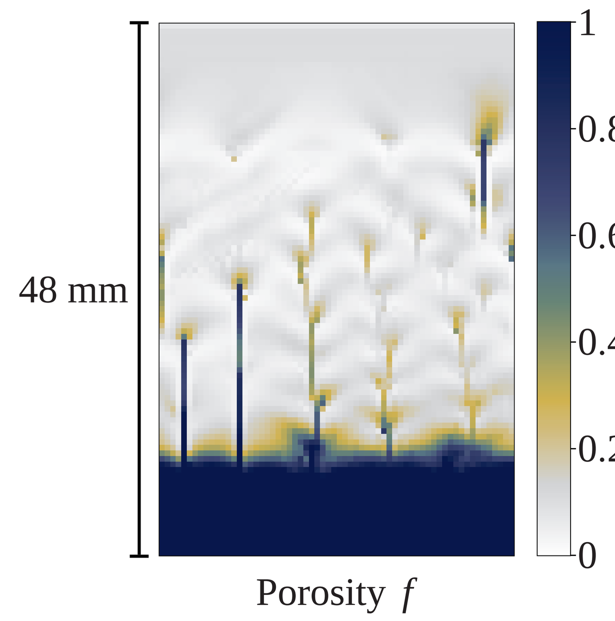
Influence of the permeability close to the ice–ocean interface: the isotropic permeability at the sea ice–ocean transition is indicated. (power law permeability–porosity relationships producing almost identical stable salinity profiles)



- The ratio V/V_i is sensitive to the permeability at the sea ice–ocean transition.

8. Sea ice–ocean transition

Simulation at high growth rate (−30 °C surface temperature); permeability after *Petrich et al.* (2006); 0.5 mm resolution. The interface is rough at the mm-scale, systems of brine channels and feeders appear.



Brine channels are remanent of preferred flow paths during desalination. Their presence causes scatter in averaged simulated data. Computations at high resolution reveal a fine structure with signs of feeder systems, showing that the system of channels and inclusions is intrinsic to sea ice. Scatter in data from continuum fluid dynamics simulations is therefore a reflection of the dynamic desalination process rather than a numerical artifact.

9. Conclusion

- Continuum fluid dynamics simulations are able to produce realistic average sea ice salinity profiles.
- The model suggests that the average salinity profile (and hence salt flux during growth) can be predicted based on the ice growth rate.
- The cumulative, maximum nutrient supply to ice algal communities can be evaluated, shedding light on patchiness and spatial differences in biomass.
- The model can be extended to the melt season to investigate brine percolation, and evolution of porosity and nutrient fluxes at the ice–ocean transition.

10. Acknowledgements and References

This work was funded by the Foundation for Research, Science and Technology (FRS&T), New Zealand. Thanks to Mats Granskog for kindly providing the stable salinity data, and to Craig Purdie for valuable discussions.

References

Eicken, H., T. C. Grenfell, D. K. Perovich, J. A. Richter-Menge, and K. Frey, Hydraulic controls of summer Arctic pack ice albedo, *Journal of Geophysical Research*, *109*, 2004.

Granskog, M. A., J. Uusikivi, A. B. Sequeiros, and E. Sonninen, Relation of ice growth rate to salt segregation during freezing of low-salinity seawater (Bothnian Bay, Baltic Sea), *Annals of Glaciology*, *44*, in press.

Nakawo, M., and N. K. Sinha, Growth rate and salinity profile of first-year sea ice in the high Arctic, *Journal of Glaciology*, *27*, 315–330, 1981.

Petrich, C., P. J. Langhorne, and Z. F. Sun, Modelling the interrelationships between permeability, effective porosity and total porosity in sea ice, *Cold Regions Science and Technology*, *44*, 131–144, 2006.